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Zhiqiang Gao

Wei Gao

Ni-Bin Chang
University of Central Florida

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Zhiqiang Gao,[a,b] Wei Gao,[a] and Ni-Bin Chang[c]

[a] Colorado State University, U.S. Department of Agriculture, UV-B Monitoring and Research Program, Natural Resource Ecology Laboratory, Fort Collins, CO 80525
gaoland@gmail.com and wgao419@gmail.com

[b] Chinese Academy of Sciences, Institute of Geographical Sciences and Natural Resources Research, Beijing,100101, China
gaoland@gmail.com

[c] University of Central Florida, Department of Civil, Environmental, and Construction Engineering, Orlando, FL, 32816
nibinchang@gmail.com

Abstract. In recent years, the risk of health effects caused by the increased exposure to Ultraviolet-B (UVB) due to stratospheric ozone depletion has received wide attention. In the US, there are two ways to accurately measure the UVB. They include: 1) the National Aeronautical and Space Administration (NASA) Nimbus-7 total ozone mapping spectrometer (TOMS), and 2) the United State Department of Agriculture (USDA) ground-based network. This paper compares these two sensors' data for the ultraviolet index (UVI) nationally and regionally to support possible public health, agricultural, and ecological analyses in the future. The major findings of our study are: 1) although there are discrepancies between these two data sets, the temporal correlation coefficients can be as high as 98%. 2) Both types of data sources depict the macroscopic spatial pattern of the UVI across the continental US.indicating a strong spatial correlation; 3) The two data sources are generally consistent though the UVI of the NASA TOMS data are often about 0.13-1.05 units larger than those of the USDA ground-based measurements; and 4) Varying differences can be seen between the Midwest and two coastal regions. While the level of the UVI on the west coast has shown a decreasing trend in the past few years, its counterpart on the east coast showed an opposite trend in between 2000 and 2005. It is hard to conclude that the changes are due to variations of total ozone concentrations in this study period. The USDA ground-based measurements may be better applied for time series analysis for public health, ecological, and agricultural applications due to their ability to provide intensive calibrated point measurements.

Keywords: UVB changes, UVI, USDA Ground-based Measurements, Nimbus-7/TOMS, spatiotemporal analysis.

1 INTRODUCTION

Changes in the Earth's atmosphere caused by anthropogenic and natural pollutants have led to a well-documented decline in ozone and a corresponding increase in ultraviolet (UV) irradiance at the Earth's surface at higher latitudes [1-4]. At lower latitudes (30.8S to 30.8N), UV radiation is highest during the summer season, because smaller solar zenith angles minimize the atmospheric path length. UV-A irradiances (320–400 nm) are not significantly affected by ozone levels because they are not strongly absorbed by ozone [5]. However, the amount of ultraviolet radiation penetrating to the Earth's surface with wavelengths shorter

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than 320 nm (UV-B) can be reduced by ozone absorption, aerosols, clouds, ground albedo, altitude and Rayleigh scattering in the atmosphere [6,7].

An increase in UV doses could lead to a variety of adverse health and environmental effects, including human health, crop yields, ocean productivity, biodiversity, and materials aging. Many of these effects are related to doses accumulated in the course of a lifetime; therefore knowledge of the changes in ground-level UV radiation over prolonged periods is required to support environmental and health risk assessments of UV radiation. For example, the thinning of the atmospheric ozone layer has led to elevated levels of UVB at the Earth's surface, resulting in an increase in health risks due to DNA damage in living organisms. Consequently, concern over the harmful effects of increased solar UV radiation on the biosphere has prompted extensive efforts to characterize it at the Earth’s surface, with the hope of identifying its impacts over differing latitudes [8-10].

Using global irradiance measurements Lapeta et al. [11] discussed the influence of ozone and temperature profiles on surface UV radiation, and on the total ozone column. Findings indicated that differences in ozone maximum height as well as in ozone concentration in the upper troposphere have a significant influence on surface UV radiation. Because the decreasing trends in ozone had already been occurring for several years before the UV radiation measurements became available, it would be of interest to compare the ground-based measurements and the TOMS satellite data at differing spatial and temporal scales across the continental US. It is known that the TOMS data had anomalies in the year 2002 and Earth Probe TOMS begun to experience two problems after 2002. To address such impacts, this paper presents a comparative analysis to examine the multitemporal trends and correlations of UVB in recent years, investigating the potential of both data sets to be applied over the continental US.

In this study, intercomparisons were made between the daily UV erythemal doses calculated with the NASA Nimbus-7/TOMS UV algorithm (Version 8.0) and from the USDA ground-based network between 2000 and 2005. Eight USDA ground stations, including AZ02 (Flagstaff, Arizona, elevation 2073 m, 36.059^{o}N, 112.184^{o}W), CA02 (Davis, California, elevation 18 m, 38.534^{o} N, 121.777^{o} W), CO02 (Nunn, Colorado, elevation 1641 m , 40.806^{o}N, 104.756^{o}W), OK02 (Billings, Oklahoma, elevation 317 m, 36.604 ^{o}N, 97.485^{o} W), IL02 (Bondville, Illinois , elevation 213 m, 40.053^{o}N, 88.372^{o}W), LA02 (Baton Rouge, Louisiana , elevation 6 m , 30.364^{o}N, 91.167^{o}W), MD02 (Queenstown, Maryland, elevation 5 m , 38.917^{o}N, 76.151^{o}W), and WA02 (Pullman, Washington , elevation 805 m, 46.76^{o}N, 117.192^{o}W) were selected for detailed investigations of the multitemporal trends and the correlations between the TOMS UV index (UVI) and the USDA UV-MFRSR UV index. This is followed by a brief spatial analysis of the multi-year UVI data computed from the TOMS and the Ultraviolet Multifilter Rotating Shadowband Radiometer (UV-MFRSR) data over the continental US. Such a study, showing the amplitude of the seasonal variation during a 6-year study period from 2000 to 2005, reveals some important information as to how the high and low-amplitude variations of the UVI are related to geographical location and elevations. It leads to a multitemporal assessment based on both data sources at the continental and regional scales, which is intimately tied with some environmental factors and is of significance for future health informatics, agricultural and ecological studies.

2 MATERIALS AND METHODS

2.1 USDA UVB data

The USDA UV-B Monitoring and Research Program (UVMRP) is a program of the US Department of Agriculture's Cooperative State Research, Education and Extension Service (CSREES). The UV-B Radiation Monitoring and Research Programs began in 1995, and 37 sites now exist across the United States. All data from the network is captured by on-site data loggers and downloaded over phone lines each evening. Data is made available to the scientific community, as well as the general public, for next day retrieval via the network's World Wide Web site (http://uvb.nrel.colostate.edu). These stations use the UV-MFRSR sensor, which is a seven-channel UV version of the visible multifilter rotating shadow-band radiometer, to measure total horizontal and diffuse horizontal irradiances. The seven channels are created by ion-assisted-deposition filters with a nominal bandwidth of 2 nm at full width half maximum (FWHM) and nominal band centers at 300, 305, 311, 317, 325, 332, and 368 nm. There is filter-to-filter variation in the nominal wavelength center. The direct beam is obtained by subtraction of the diffuse horizontal from the total horizontal irradiance and includes corrections, such as Langley calibration. The measurement is completed in less than 5s at all wavelengths. All three components are recorded every 20s and averaged to 3-min intervals.

The broadband UVB-1 Pyranometer employed (Yankee Environmental Systems, Turners Falls, MA 01376 USA), measures global irradiance in the UVB spectral range of 280-320 nm. Fig. 1 shows the locations of all 37 ground-based stations and highlights the eight sites (circled sites) selected for a detailed multitemporal analysis, covering the stations AZ02, CA02, CO02, OK02, IL02, LA02, MD02, and WA02. These eight stations are well distributed geographically, with WA02 located in the north, LA02 in the south, MD02 in the east, CA02 in the west, and others in the central states.

2.2 TOMS Data

In contrast to ground observations, satellites provide complete global coverage at a moderate resolution with standardized sensors. UV has been observed from space for more than 30 years. Early satellite UV measurements were made by the Backscatter Ultraviolet (BUV) sensor onboard the Nimbus 4, which was launched in 1970 and continued functioning for several years. Nimbus 7 provided the longest high-quality UV space-borne observation from 1978 to 1993 with TOMS. This dataset can be used for monitoring long-term trends in total column ozone. Further, it is useful for investigating seasonal chemical depletions in ozone occurring in both the southern and northern hemisphere polar springs [15-17].

The Erythemal Exposure data product of TOMS is an estimate of the daily integrated ultraviolet irradiance, calculated using a model of the susceptibility of caucasian skin to sunburn (erythema). This can be interpreted as an index of the potential for biological damage due to solar irradiation, given the column ozone amount and cloud conditions on each day. The Erythemal Exposure (Exp) is defined by the integral [18]:

$$\mathrm{Exp} = \frac{1}{d_{es}} \int_{280\mathrm{nm}}^{400\mathrm{nm}} d_{\lambda} S(\lambda) W(\lambda) \int_{t_{ss}}^{t_{sr}} d_t C(\lambda, \vartheta, \tau_{c1}) F(\lambda, \vartheta, \Omega)$$

where d_{es} is the Earth-sun distance, in A.U.; S is the solar irradiance incident at the top of the atmosphere at 1 A.U. (nW m-2 nm-1); W is the biological action spectrum for erythemal damage, in B.D. m-2; t_{sr} and t_{ss} are the time of sunrise and sunset, in radians; C is the cloud attenuation factor, unitless;τ_{cl} τ_{c1} is the cloud optical thickness, in mbar; ϑ is the solar zenith angle (function of time, t), in radians; and F is the spectral irradiance at the surface under clear skies, normalized to unit solar spectral irradiance at the top of the atmosphere, unitless.

2.3 UV-Index (UVI)

For UV induced erythema (sunburn), the action spectrum adopted by most international organizations is the CIE (Commission Internationale de l'Éclairage, International Commission on Illumination) action spectrum (E), using the method described by *McKinlay and Diffey* [19, 20]. The UV-Index (UVI) itself is an irradiance scale computed by multiplying the CIE irradiance in watts m^{-2} by 40. The clear sky value at sea level in the tropics is normally in the range 10-12 (250-300 mWm^{-2}) and 10 is an exceptionally high value for northern mid-latitudes. This scale has been adopted by the World Meteorological Organization (WMO) and World Health Organization (WHO) and is in use in a number of countries. The UV intensity is also described in terms of ranges running from low (0-2) to medium (3-5), high (6-7), very high (8-10) and extreme values (11+) [3, 21-22].

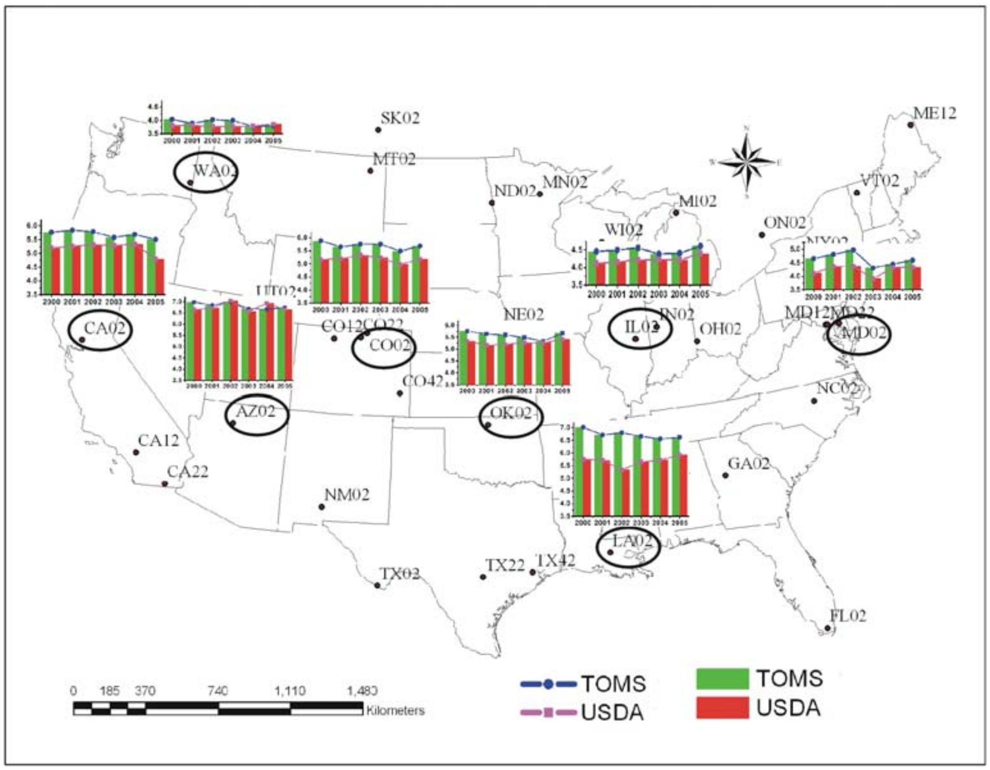


Fig. 1. Map of the 37 USDA ground stations. (Statistical analyses were performed only on the eight circled stations).

3 RESULTS AND DISCUSSION

3.1 Yearly Analysis of the UVI trend

The yearly averaged dataset was generated to produce the bar charts overlaid by line graphs associated with these eight stations. As shown in Fig. 1, the UVI of TOMS data measured over the eight stations are always higher than those collected by USDA stations. The difference in these UVI values between TOMS and USDA data at LA02 station was the largest. The difference of six-year average UVI was 1.04 and relative difference was 15%. On the other hand, the difference of these UVI values between TOMS and USDA data at AZ02 was the smallest. The difference of six-year average UVI was 0.06 and relative difference was 0.88%. Yet the difference of six-year average UVI over the rest six stations was in a range of 0.12~0.49, and the relative difference is in a range of 3.05%~9.13%. Overall, the UVI values between TOMS and USDA data seem very close.

Both UVI data sets collected, USDA and TOMS, in these three stations (WA02, IL02, and MD02) in the northern states exhibit relatively smaller values. The smallest was collected at WA02 and its UVI values ranged from 3.77 to 4.04. Both UVI data sets collected by USDA and TOMS around the five stations in south-central and western regions of the Continental US were larger. The UVI measurements in both TOMS and USDA data sets at LA02 were the largest – UVI values ranged from 5.33 to 7.02. As a consequence, as expected, the UV radiation exhibits an increasing trend from northern states to southern states over the Continental US.

The line graphs revealed that three out of eight stations, including CO02、IL02 and CA02, showed consistent trends between yearly TOMS and USDA data sets. Yet the trends were inconsistent over the rest of five stations within the period of 2000-2005. It is interesting to look into the drastic fluctuations over 1-2 years which particularly altered the entire trends. Between TOMS and USDA data sets, the trends at CO02, MD02, OK02 and CA02 stations were consistent and the trends over the other three stations were inconsistent during the period of 2003-2004. Some stations, such as MD02, CO02, and CA02, presented a sharp decrease of the UVI values in 2003-2004 due to unknown reasons independent of which data sets we followed.

3.2 Monthly Comparative Analysis of the UVI seasonal changes

For the eight representative ground-based stations, we produced the derived daily UVI data measured by the broadband UVB-1 Pyranometer and the TOMS instrument from 2000 to 2005 for statistical analyses (Table 1) [13]. Table 1 summarizes the mean, median, maximum, standard error, standard deviation, and correlation coefficients of the UVI for these two datasets, revealing how they vary relative to the mean and their correlations with each other.

Table 1 also shows that the mean absolute disparity between the UVI data derived from the ground-based stations and the TOMS data ranged from 0.13 (OK02) to 1.05 (LA02) units. The relative disparity between the two sources ranged from 2% to 15%. The maximum of the UVI based on these two sources are, however, very close. Their absolute disparity ranged from 0 (IL02) to 1.62 (LA02) and the relative disparity between the two sources ranged from 0% to 15% during the study period. Correlation coefficients between the two sources are > and 98%, indicating that they are highly correlated temporally. These summary statistics reveal that the degree of consistency between the two data sources. It may be concluded that the mean, median, and maximum of the multi-year UVI time series are very close between these two sources. Both standard errors and standard deviations are very similar across the eight stations, indicating that similar fluctuations due to planetary- and medium-scale waves occurred at these sites during the study period. Such findings support advanced spatial analyses. To compare monthly variations, the scatter plots over the eight stations between 2000 and 2005 are presented in Fig. 2. Over these eight stations, the UVI seasonal changes are very close between the USDA and the TOMS data sets, as evidenced by those correlation coefficients between these two data sets (i.e., more than 98%).

Both WA02 and IL02 stations are closely located in northern states. Figures 2(a) and 2(d) may visually support the claim that the amplitudes of the UVI seasonal variation associated with the TOMS and USDA data sets are very close. Based on the seasonal data of these two stations between 2000 and 2005, the TOMS UVI was larger than its 11 counterpart by about 0.05-0.65 and the relative differences were in between 1.09% and 10.62% in spring, summer, and autumn. In winter, however, the USDA UVI data were larger by about 0.22 and 0.26, and the relative differences were between 19.48% and 28.45%. Only the WA02 and IL02 stations showed that the USDA UVI data were greater than those of TOMS UVI data in winter.

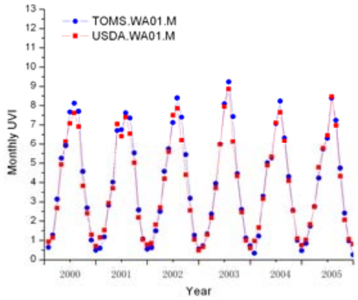
The three stations OK02, CO02, and AZ02 are located in the central region of the continental US; the OK02 station is located in the Great Plains with a lower elevation and the remaining two stations are located at the Plateau with much higher elevation (i.e., more than 1,600 m). In spring and winter, the TOMS UVI data were larger by about 0.06-0.32 and the relative differences varied from 2.66% and 4.97% relative to the USDA UVI data. Within these three stations, the USDA UVI data collected at AZ02 station are larger than the counterparts of the TOMS data in spring. In summer and autumn, the UVI difference between these two data sources at the CO02 station was the highest. The difference of UVI values in between these two data sources are 0.13-1.22, and the relative differences varied from 1.2% to 12.61%.

Table 1. Monthly statistical analysis of UVI TOMS and USDA data.

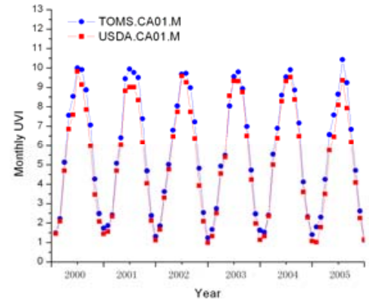
	WA02		CA02		CO02		*AZ02*	
	USDA	TOMS	USDA	TOMS	USDA	TOMS	USDA	*TOMS*
Maximum	8.86	9.22	9.82	10.43	9.82	10.97	12.14	*11.36*
Mean	3.80	4.00	5.20	5.69	5.20	5.80	6.76	*6.94*
Median	3.42	3.98	5.20	5.51	5.20	6.18	7.13	*7.60*
Std. Error	0.30	0.33	0.34	0.36	0.35	0.38	0.38	*0.38*
Std. Deviation	2.53	2.74	2.95	2.56	2.95	3.15	3.22	*3.16*
Correlation Coefficient	*0.99*		*0.99*		*0.98*		*0.98*	
	IL02		OK02		MD02		LA02	
	USDA	TOMS	USDA	TOMS	USDA	TOMS	USDA	TOMS
Maximum	8.51	8.51	9.68	9.95	7.6	8.19	8.73	10.35
Mean	4.22	4.48	5.57	5.70	4.24	4.71	5.68	6.73
Median	4.21	4.57	5.20	6.18	3.81	4.95	5.87	7.15
Std. Error	0.65	0.30	0.31	0.32	0.25	0.29	0.23	0.30
Std. Deviation	2.25	2.56	2.61	2.75	2.15	2.35	2.00	2.45
Correlation Coefficient	*0.99*		*0.99*		*0.98*		*0.98*	

The MD02 station is located in the eastern part of U.S. whereas the CA02 station is located at its western part. The LA02 is located in between in the southern part of U.S. The elevations of these three stations are lower than 18 m which implies the elevation has little differential effect in terms of the altitude on the UVI among them were with. The findings of these three stations include: 1) the TOMS UVI data in autumn were notably higher than the counterpart data collected by the USDA stations; the differences are between 0.51and 0.94. The relative differences varied between 12.88% and 15.78%. The UVI differences in winter between the TOMS and the USDA data at CA02 and LA02 stations are much larger. This observation can be evidenced by the fact that differences varied from 0.26 to 0.4 and the relative differences are between 10.91% and 13.70%. However, the UVI differences in spring and summer are notably smaller. This is because the difference in between varied from 0.39 and 0.64 and the corresponding relative differences are in between 6.95% and 7.85%. The UVI differences in spring and summer between the TOMS and the USDA data at LA02 station are very large over all the other stations. In this case, our record shows that differences between them varied from range of 1.01 to 1.82 and the relative differences were between 12.47% and 19.60%.

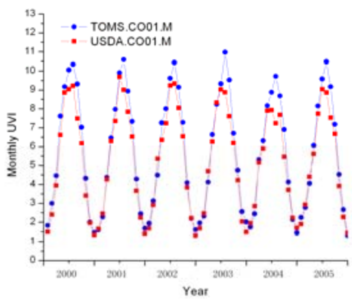
In summary, the UVI differences between the TOMS and the USDA data were very large in autumn and winter. However, it became relatively smaller in spring and summer. In all seasons, the UVI differences at LA02 station were higher than the rest of the stations. But the TOMS UVI data in winter were smaller than that of USDA data at WA02 and IL02 located in the northern states, whereas the TOMS UVI data were generally larger than that of USDA data in the rest of stations.



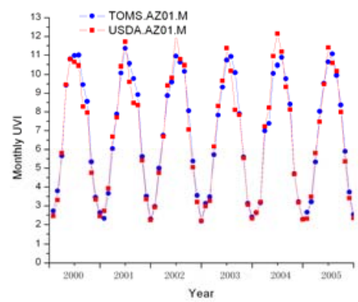
(a). UVI changes in WA02 station.



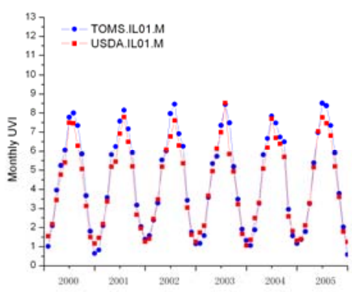
(b). UVI changes in CA02 station.



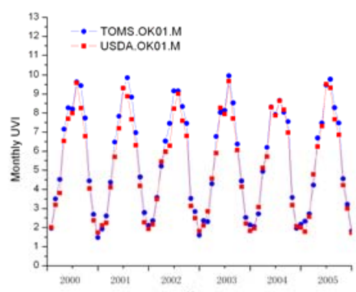
(c). UVI changes in CO02 station.



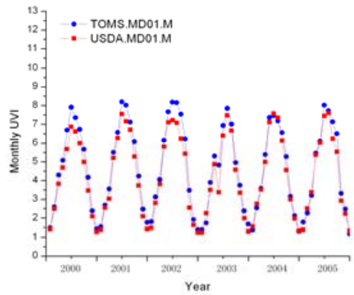
(d). UVI changes in AZ02 station.



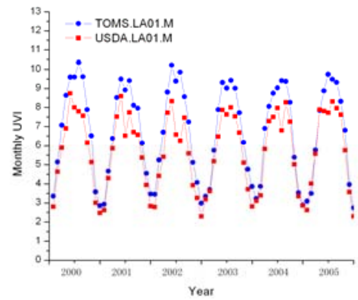
(e). UVI changes in IL02 station.



(f). UVI changes in OK02 station.



(g). UVI changes in MD02 station.



(h). UVI changes in LA02 station.

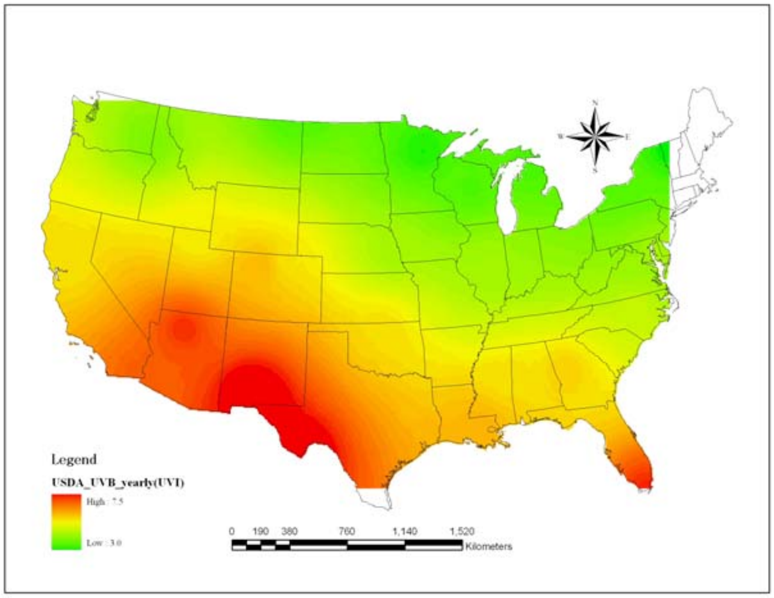
Fig. 2. Comparative temporal analysis of UVI between two data sources from 2000 – 2005.

We are also interested in knowing more about the increasing or decreasing trends over the 6-year time period. Figure 2(d) confirms the consistency of the general trend between two data sources at AZ02 station. It uniquely shows that the UVI is increasing from 2000 to 2002, then decreasing between 2002 and 2003, and experiences different types of changes associated with two data sources from 2003 to 2005. The TOMS UVI data show a slightly increasing trend although only a trivial difference can be seen between the two data sources having a mean difference of 0.05. This implies that the TOMS UVI data were only 0.68% higher than that of the USDA ground-based measurements during the study period. Figure 2(g) shows the comparison at the Maryland station (MD02). The trend of UVI of the TOMS data and the USDA ground-based measurements is similar, although there is a distinctive difference between these two datasets.

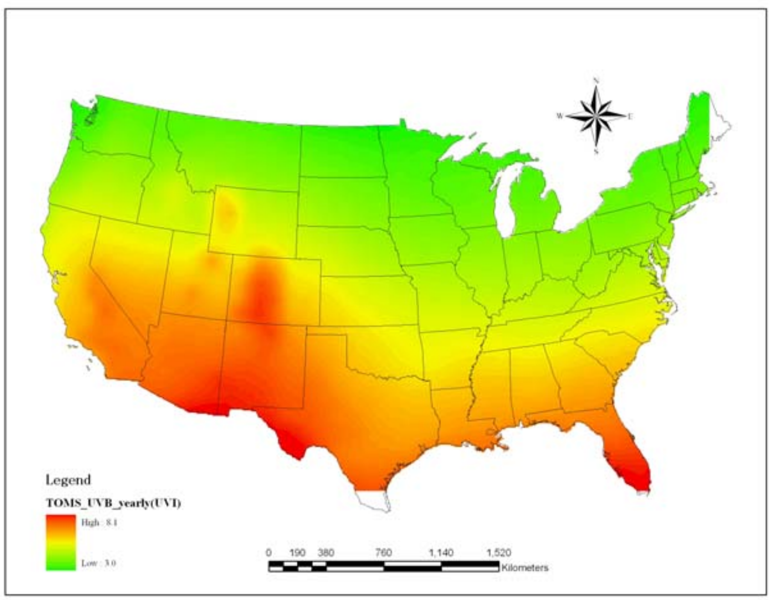
While the former showed a significant increase from 2000 to 2002, the latter decreased from 2002 to 2003. Then the UVI of both data sources between 2004 and 2005 had a similar increasing trend. Overall, both the NASA and the USDA UVI show an average difference of 0.47 within the 6-year time frame. On average, the TOMS UVI is 11.0% higher than that of the USDA ground-based measurements.

Figure 2(c) reflects a similar decreasing trend between these two data sources except for 2000-2001 at the Colorado station (CO02). The average difference of the UVI between these two data sources is 0.52 within the 6-year time frame. The average TOMS UVI is 10.05% higher than that of the USDA ground-based measurements on average. Yet this is not the case at Washington station (WA02). Figure 2(a) reveals a much different trend of the UVI except in the time period of 2004-2005. In general, while the USDA UVI was increasing slightly over time, the TOMS UVI showed a significantly decreasing trend. The average difference of the UVI between these two data sources is 0.1 within the 6-year time frame. On average, the TOMS UVI is 2.63% higher than that of the USDA ground-base measurements.

Overall, although the TOMS UVI and the USDA UVI showed a high degree of correlation (e.g., correlation coefficients are 98% and above), the average difference of the UVI within a 6-year time frame varies from 0.13 to 1.05. In most cases, the UVI variations follow a much different pattern between these two data sources across various stations. In short, only a few stations such as CO02 and CA02 show a consistent trend in the UVI. The three stations located at northern states exhibited smaller average difference in between these two UVI datasets. Yet all of them showed weaker UVI in northern states over the seasons. On the contrary, these five stations located at southern or southeastern states exhibited bigger average differences between these two UVI datasets. Yet all of them showed stronger UVI in southern or southeastern states over the seasons. With the of the LA02 station that exhibited larger average difference, all the remaining seven stations only reveal mild average differences within a range of 10%.



(a). USDA ground-based measurements.



(b).TOMS satellite data.

Fig. 3. Maps of UVI spatial distributions based on multi-year average (2000-2005).

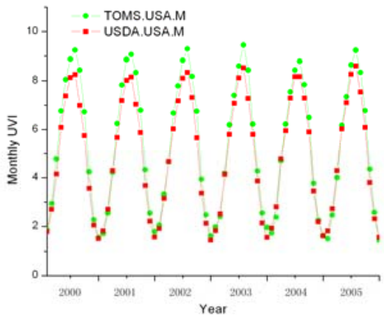
3.3 Comparative spatiotemporal analysis

Spatial patterns of the UVI revealed by both data sources were also compared at 4×4 km spatial resolution using the Geographical Information System (GIS). Spline interpolation in GIS (Arc/Info) was used to generate the UVI map based on USDA point measurements. The northeastern area (i.e., the New England region) lacked actual data available for interpolation resulting in a blank at the upper right corner on the map. The two data sources portray very similar spatial distributions of the yearly UVI (Fig. 3). In the USDA ground-based measurements, the maximum of the UVI is 7.5. The area where the UVI values exceed 6 accounts for 13.7 percent of the total study area. It occurs between the south of New Mexico and Texas and at the southern tip of Florida. In the TOMS data sets, the maximum of the UVI is 8.1. The area where the UVI values exceed 6 accounts for 31.7 percent of the total study area. It covers almost all southern states in the Gulf of Mexico region up to the southern Colorado plateau. The minimum UVI is 3.0. With the USDA ground-based measurements, the area where the UVI values are less than 4 accounts for 23.5 percent of the total study area, and it is mostly located around the northern states and the Great Lakes region. With the TOMS data, however, the area where the UVI values are less than 4 accounts for 22.4 percent of the total study area, and it is mostly located around the northern states and the Great Lakes region, too.

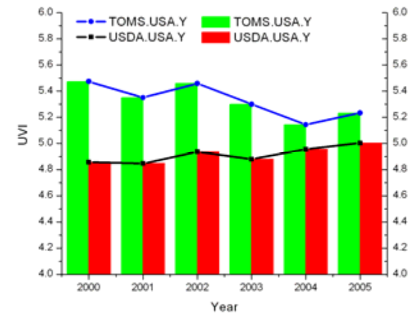
From a statistical point of view, the mean of the USDA ground-based measurements and the TOMS data is 4.9 and 5.3, respectively. The standard deviation of the UVI values based on these two data sources is 0.97 and 1.28, respectively. From the minimum and maximum values associated with both data sources, it can be concluded that the TOMS data may exhibit more reflective spatial patterns in response to the terrain complexity. Due to the restrictions of surface observations, the UVI distribution based on the USDA ground-based measurements shows less sensitivity in response to topographic features and terrain complexity. This is especially true at the Colorado Plateau.

With the USDA ground-based measurements and the TOMS data, it is indicative that the distribution of the UVI appears to be strongly tied with latitude and topography simultaneously. The higher the latitude, the smaller the UVI value (Fig. 2 and 3). The maxima of yearly UVI values appeared along the middle latitudes of Arizona, New Mexico, Texas, and southern Florida whereas the minima of them showed up across the upper latitudes of the Great Lakes region and the Central Lowland area. The UVI values were also greatly influenced by the topography from east to west. Along the same latitude, the UVI values in the east were normally smaller due to lower altitudes, while the UVI values in the west were larger due to higher altitude. Overall, as a result of the integrated effects of both latitude and altitude, the UVI distribution patterns show a characteristic trend of high values in the southwest and low values in the northeast.

Having the monthly scatter plots and the yearly mean data of the TOMS and USDA data over the entire study period summarized, Fig. 4 shows that the comparative amplitudes of the seasonal variations between these two data sources were obviously not consistent in 2002-2004. The UVI means of the TOMS and USDA data in winter were extremely close, as evidenced by the values of 2.041 and 2.042, respectively. The difference of the UVI means in between is around 0.1% from which the USDA data are seen to be slightly larger than those of the TOMS data. The UVI mean of the TOMS data in spring was larger as evidenced by a value of 0.32 from which the TOMS data were 5.04% larger than that of the USDA data. The UVI mean of the TOMS data in summer remained larger by a value of 0.81 whereas the TOMS data show a difference of 9.27% larger compared to the USDA data. The UVI mean of the TOMS data in autumn was still larger by a value of 0.53; the TOMS data show a difference of 11.96% larger than that of the USDA data.



(a). Monthly UVI Changes of USDA and TOMS.



(b). Yearly UVI changes of USDA and TOMS.

Fig. 4. The spatial monthly and annual mean of the UVI with respect to both data sources over the continental US.

Table 2. The spatial annual mean of the UVI associated with two data sources over the continental US.

Year	TOMS	USDA	Dif	P%
2000	5.47	4.83	0.64	13.29
2001	5.34	4.82	0.52	10.84
2002	5.45	4.91	0.54	11.07
2003	5.26	4.85	0.41	8.42
2004	5.14	4.93	0.21	4.35
2005	5.23	4.97	0.26	5.14
Mean	5.33	4.89	0.44	8.90

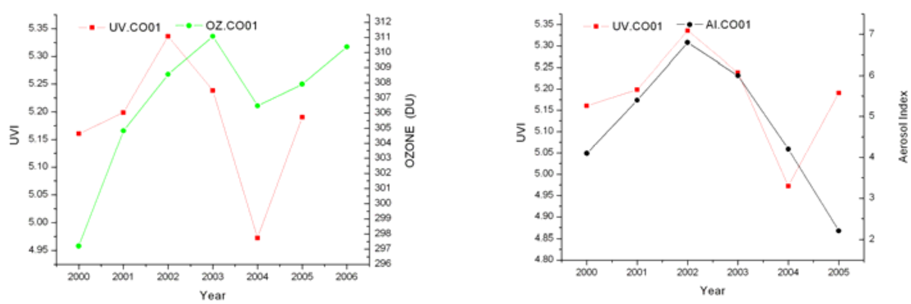
Note: Dif = TOMS – USDA, P% = Dif / TOMS * 100.

Within Fig. 4, an opposite trend was confirmed possibly due to anomalies in the TOMS data in the year 2002 and thereafter when Earth Probe TOMS began to experience problems after 2002. Between 2000 and 2003, the TOMS data showed a decreasing trend, followed by a cyclic trend, while the ground-based measurements revealed the same increasing trend. In the time period from 2004-2005, the UVI derived from these two data sources revealed a significant increasing trend simultaneously. Only in the period 2003-2004, there is an inconsistent trend of the UVI values when comparing both TOMS data and USDA data. In all comparable periods i.e., 2000-2005, it can be concluded that the UVI was increasing based on the USDA ground-based measurements, but was decreasing based on the TOMS data. The TOMS data may respond to the topography and latitude and embody the spatial distribution patterns and characteristics of the UVI easily whereas the USDA data offered point measurements that represent the ground truth values.

Table 2 thus summarizes the spatial mean of the UVI derived from both TOMS and USDA data over the entire continental US. They are 5.33 and 4.89, respectively. The difference is 0.44. The UVI of TOMS data is 8.9% larger than that of USDA data. According to Table 2, the difference between these two data sources generally decreased over time indicating that NASA had gradually fixed the problems. Overall, the percentage changes of the UVI derived by both TOMS and USAD data dwindled to a difference of smaller than 10% by the end of the study period.

3.4 Environmental effects: ozone, aerosol, and cloud

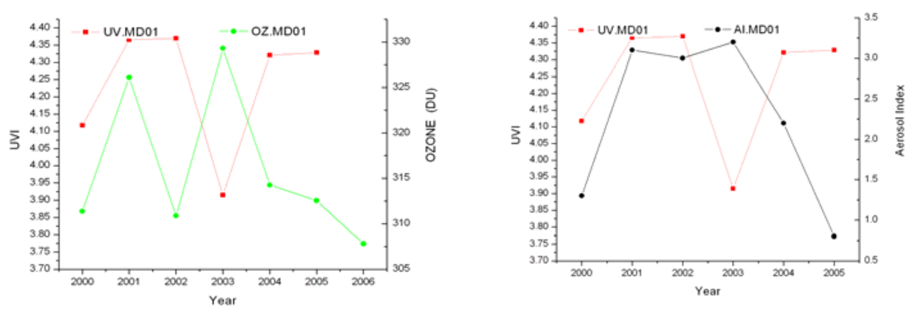
Many environmental factors such as ozone, aerosol, and cloud may affect UV irradiance [23-25]. In addition to the total ozone content that is interrelated with changes of solar radiation in the near ultraviolet wavelengths, the second largest cause of temporal and geographic variability of UV irradiance is clouds [26]. The next one could be the atmospheric aerosol particles that reduce the UV irradiance due to the aerosol scattering effect causing reduction of UVI increases with aerosol optical depth. According to the findings in preceding sections, two scientific questions remain concerning the spatiotemporal variations of the UVI across the continental US can be summarized for the extended study of the environmental effects as below: 1) why some stations, such as MD01 and CO01, presented a sharp decrease of the UVI during the 2003-2004 time period? And 2) why the UVI decreased at the west coast but increased at the east coast over the study period generally? To answer these two questions, three additional sets of data are required: 1) the total ozone data derived from the USDA ground stations, 2) the total cloud data derived from the International Satellite Cloud Climatology Project (ISCCP), and 3) aerosol index data derived from TOMS Version 8.0 (Total Ozone Mapping Spectrometer). Further, aerosol column absorption measurements using co-located UV-MFRSR and Shadowband Radiometer (MFRSR) instruments of the USDA UV-MFRSR may provide us with an additional source of aerosol data if TOMS Version 8.0 (Total Ozone Mapping Spectrometer) should have anomalies.



a. UVI and total ozone at CO02 station

b. UVI and aerosol index at CO02 station

Fig.5. Scatterplots of UVI, total ozone and aerosol index at the CO02 station.



a. UVI and total ozone at the MD02 station .

b. UVI and aerosol index at the MD02 station.

Fig.6. the scatter plots of UVI, total ozone and aerosol index at MD02 stations.

The reasons for the drastic decrease in the UVI in the period of 2002-2004 at CO02 and 2002-2003 at MD02 stations might be due to the seasonal or annual changes in total ozone, these could affect, the pure aerosol effect, and/or even the integrated aerosol effect on cloud. Besides, the fact that UVI decreased on the west coast but increased on the east coast over the study period might be due to the altitude effect in addition to the possible changes over total ozone, total cloud and aerosol. In the spirit of finding out the true reasons for the appearance of such spatiotemporal variations over time, the following analysis is geared toward answering these two questions sequentially based on the above hypotheses.

The UVI derived at both stations did not show any correlation with total cloud. Hence, the scatter plots of the UVI versus the associated total ozone and aerosol index at CO02 and MD02 stations may be summarized in Fig. 5 and 6, respectively. With such a comparison, it can be concluded that UVB radiation drastically reduced and UVI sharply decreased at the CO02 station in the period from 2002-2004, while total ozone increased from 2000-2003 followed by a mild decrease during the time period of 2003-2004. Later, the total ozone rose again. But aerosol index declined in the same period (2002-2004) after reaching its peak value at 2002. It seems that the major driving force making the UVI decrease in 2002-2004 was due to the increase of total ozone. At the MD02 station, the UVB radiation decreased significantly during 2002-2003, then increased significantly during 2003-2004, and rose slightly during 2004-2005. Such phenomena might be due to the fact that the total ozone increased significantly during 2002-2003 and decreased evidently during 2003-2004. It decreased again slightly during 2004-2006. The aerosol index increased slightly during 2002-2003, and then sharply declined during 2003-2005. It seems that the total ozone and aerosol collectively played a major role impacting on the decrease of UVB radiation obviously in 2002 and 2003. Based on the comparative analysis above, it can be concluded that the sharp decrease of UVB at CO02 and MD02 stations was mainly caused by the total ozone in 2002-2004 and in 2002-2003, respectively.

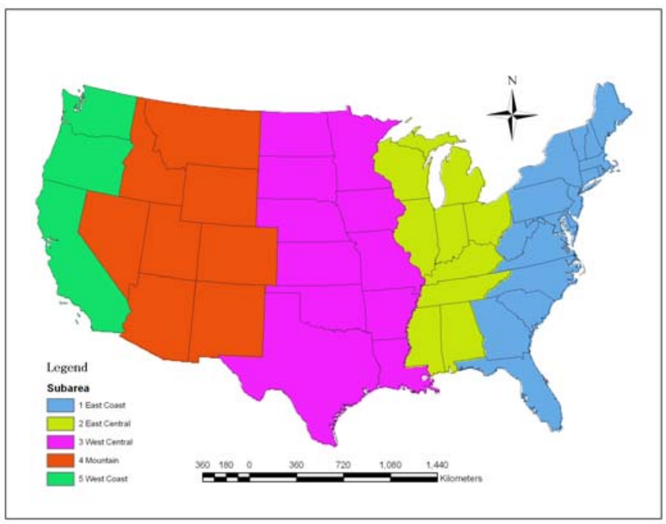
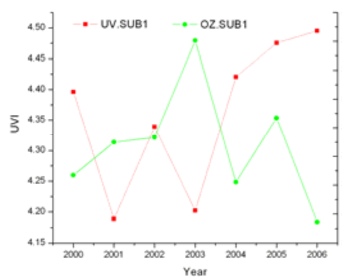


Fig. 7. The five Geographical regions of the continental US in this study.

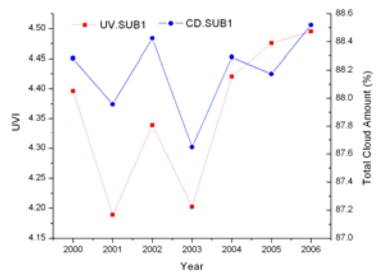
To simplify our discussion, the US continent can be geographically divided into five regions as shown in Fig. 7: 1) East Coast including New England (Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island, Vermont), Middle Atlantic (New Jersey, New York, Pennsylvania), and South Atlantic (Delaware, Region of Columbia, Florida, Georgia, Atlanta, Maryland, North Carolina, South Carolina, Virginia, West Virginia), 2) East Central including East North Central (Illinois, Indiana, Michigan, Detroit, Ohio, Wisconsin), and South East Central (Alabama, Kentucky, Mississippi, Tennessee), 3) West Central including West North Central (Iowa, Kansas, Minnesota, Missouri, Nebraska, North Dakota, South

Dakota), and West South Central (Arkansas, Louisiana, Oklahoma, Texas), 4) Mountain area (Arizona, Colorado, Idaho, Montana, Nevada, New Mexico, Utah, Wyoming), and 5) West Coast (California, Oregon, Washington). Consequently, the parameters of UVI, total ozone, total cloud and aerosol index may be extracted corresponding to these five regions in the study period of 2000-2006 to analyze the reasons why the UVB increased on the east coast of the US and decreased on the west coast.

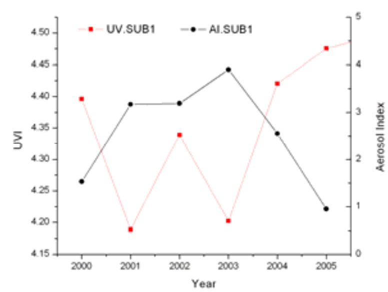
Figure 8 summarizes the comparative analysis. On the east coast area, the UVB obviously changed in accordance with the changes of total ozone. The UVB decreased between 2002 and 2003, and then increased significantly in the period 2003-2006. The total ozone increased sharply in 2002-2003, but increased slightly in 2004-2005 mixed with a sharp decrease in the time periods 2003-2004 and 2005-2006. It can be seen that when the UVB significantly increased in 2003-2006 the total ozone significantly decreased in the same time period whereas the aerosol followed a significant decline and the total cloud showed an increasing trend. Therefore, the reason for the larger UVB radiation on the east coast appears to be due to smaller total ozone and aerosol at the same time. The cloud cover seems not to have been influential on the UVB radiation in that time period.



a. UVI and ozone on the east coast



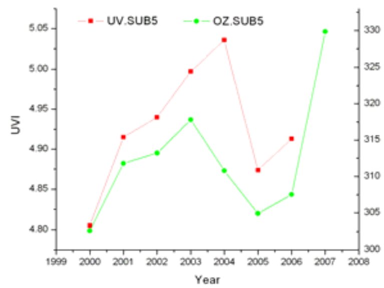
b. UVI and cloud on the east coast



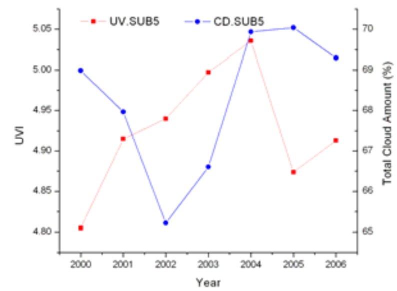
c. UVI and aerosol index on the east coast

Fig.8. Scatter plots of UVI, total ozone, total cloud amount and aerosol index on the east coast.

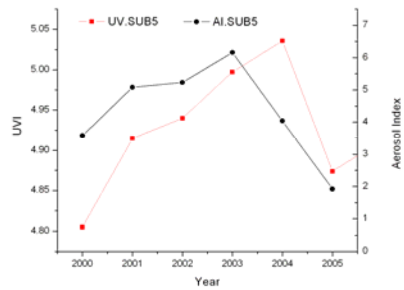
Figure 9 reveals the multitemporal patterns on the west coast. It shows UVB radiation significantly increased in 2000-2004, and decreased evidently in 2004-2005, and then increased slightly in 2005-2006. The total ozone, however, did not follow the same trend in 2003-2004. It showed the same trend in the rest of the study period, however. The changes of aerosol in 2000-2005 were consistent with the changes of UVB making them not correlated in terms of UVB variations. On the other hand, the total cloud increased significantly in 2002-2005 and decreased slightly in 2005-2006, making the changes of total cloud opposite to that of UVB in this time period. It can be concluded that the reason for having decreased UVB after 2004 was caused by a larger total cloud in this region. Overall, the TOMS data are satellite-based remotely sensed data with a resolution of 1 × 1.25 degree, and may thus receive less impact from cloud cover, rainfall, humidity, ozone, and aerosols in the air [30-33].



a. UVI and total ozone on the west coast



b. UVI and total cloud amount on the west coast



c. UVI and aerosol index on the west coast

Fig.9. Scatter plots of UVI, total ozone, total cloud amount and aerosol index on the west coast.

4 CONCLUSIONS

The difference between TOMS and USDA UVI data sets were analyzed and the spatiotemporal trends within 2000 and 2005 were fully examined with respect to both monthly and yearly scales. The inclusion of eight USDA stations selected for intercomparison, enables us to summarize the features of the multi-year UVI variations based on the basic statistical analyses including the mean, standard deviation, correlation coefficients, and the average differences. In general, these two data sources present a high degree of correlation (e.g., correlation coefficients are 98% and above); the 6-year average difference based on the time series data across the eight stations ranges from 0.13 to 1.05. However, the TOMS UVI is 2%-15% larger than that of the USDA UVI which could be due to the TOMS data which showed anomalies in the year 2002 and Earth Probe TOMS begun to experience technical problems after 2002. Such differences between the two data sources in terms of both spatial and temporal characteristics are mainly due to the fact that the TOMS data are satellite-based remotely sensed data with a resolution of 1 × 1.25 degree receiving less impact from cloud cover, rainfall, humidity, ozone, and aerosols in the air. UVB radiation is normally reflected, scattered, and absorbed before reaching the land surface. As a consequence, the USDA ground-based measurement apparatus could be significantly affected by the climatic factors such cloud cover, rainfall, temperature, as well as aerosols, ozone, and many other factors. Such findings account for the fact that the USDA ground-based measurements are often lower than those of the TOMS data.

Although both types of data can depict the macroscopic spatial and temporal patterns of the UVI over the continental US, the TOMS data may capture finer-scaled features. The TOMS data can respond to the topography and latitude, and embody the spatial patterns and characteristics of the UVI easier.

Most of stations showed less difference in autumn and winter, however. Geographically, the UVI were smaller in northern states and such difference was getting larger in central and southern states based on both TOMS and USDA data sets. According to the monthly data over the same study period, the UVI seasonal patterns were basically similar and the magnitude of seasonal changes was also pretty close no matter which data sets were employed. Under any circumstances, the TOMS UVI was always larger than that of the USDA UVI. Yet the situation is generally tempered in western and northern regions. In general, the UVI annual mean based on the NASA TOMS data is always higher than that based on the USDA ground-based measurements (i.e., 0.21-0.64 units). The UVI multi-year mean gradually decreased northward and the contour lines were approximately parallel with the latitudes, thereby presenting a convex shape to the north because of the topographical influence. As a consequence, the annual fluctuations of the UVI had an obvious association with the topography. This implies that the annual fluctuations of the UVI are larger at relatively higher altitudes.

Nevertheless, the USDA ground-based measurements may be better applied for time series analysis due to the capability to conduct intensive point measurements. The TOMS UVI data that are often 0.21-0.64 units larger than the USDA ground-based measurements may be more applicable to explore the regional patterns of UVI distribution due to higher spatial resolution and sensitivity to the topography. Finally, the environmental effects due to total ozone, aerosol, and total cloud revealed that the sharp decrease of UVB at CO02 and MD02 stations was mainly caused by the total ozone in 2002-2004 and in 2002-2003, respectively. While east cost USA experienced the increased UVB that was mainly due to the changes of the total ozone and aerosol, west coast of the USA experienced the decreased UVB that was mainly due to the changes of total cloud.

Acknowledgments

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